

# Charge-free etching process using positive and negative ions in pulse-time modulated electron cyclotron resonance plasma with low-frequency bias

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Charge build-up on a substrate is greatly reduced by using a pulse-time modulated electron cyclotron resonance generated plasma of more than 50  $\mu\text{s}$  with 600 kHz radio frequency (RF) substrate bias. Negative ions are generated in the afterglow plasma due to decay in electron temperature. Low-frequency RF bias directly accelerates both negative and positive ions from the plasma onto the substrate and reduces self-bias voltage, thus reducing charge accumulation on the substrate. This method shows promise for charge-free etching processes in the production of ultra large scale integrated circuits. © 1996 American Institute of Physics. [S0003-6951(96)04617-8]

High-density plasma, such as electron cyclotron resonance (ECR) plasma, inductive coupled plasma (ICP), and helicon wave plasma, has been used to fabricate devices for use in ultra-large-scale integrated (ULSI) circuits. However, these plasma sources cause charges to accumulate on the substrate, which could cause serious problems<sup>1,2</sup> such as local side etching ("notching") in polycrystalline silicon etching,<sup>3</sup> microloading in Si trench etching,<sup>4</sup> and gate oxide breakdown in metal-oxide-silicon (MOS) devices.<sup>5-7</sup> In particular, the degradation of gate oxides is the most serious problem due to continuous reduction in oxide thickness. This charge accumulation is caused by the difference in mobility between electrons and positive ions,<sup>8</sup> so it creates a sheath potential at a surface. To solve these problems, it is necessary to etch with bipolar ions (positive and negative ions) to eliminate the sheath potential and mobility difference between charged particles.

Pulse-time modulated (ECR) plasma is known to have many advantages due to its ability to generate a large quantity of negative ions under low electron temperature and has exhibited highly anisotropic, highly selective, high etch rate and notch-free polycrystalline silicon etching.<sup>9-11</sup> Pulse-time modulated plasma shows promise as a candidate for chargeless processes.

This letter reports on a charge-free etching process that uses negative and positive ions in pulse-time modulated ECR plasma. By enlarging the pulse interval to more than 50  $\mu\text{s}$ , a large quantity of negative ions is generated. These negative ions remain until the next discharge. As a result, the plasma consists of both negative and positive ions with few electrons. These positive and negative ions can be directly accelerated onto the substrate surface by a low-frequency bias of less than 600 kHz, thus eliminating or reducing the sheath potential and reducing charge build-up on the substrate.

ECR plasma with large diameter can be produced by a flat disk type compact plasma source (Nichimen Co., 300DFECR) with permanent cylindrical magnet arrays 300 mm in diameter and 800 mm high.<sup>4,12</sup> Microwave power at 2.45 GHz is fed through a flat waveguide to a disk type slot antenna in front of the magnet array. This propagates along the field in whistler mode and produces high-density ( $10^{11}$  cm<sup>-3</sup>) plasma near the resonance region even under

low pressure. The gas is Cl<sub>2</sub> (50 sccm). Discharge pressure is set at 3.8 mTorr. A substrate holder is located 10 cm downstream from the antenna surface. A radio frequency (rf) bias of 600 kHz is supplied to the substrate to accelerate both positive and negative ions from the plasma. Pulse-time modulated microwave power (2.45 GHz) is generated by a klystron source (Nihon Koshuha Co., NEC LD-7909) and input power is set at 1 kW. The pulse duration/interval time (duty ratio: 50%) is modulated from 0 to 100  $\mu\text{s}$  through a function generator and pulse circuit. The degree of charge on the substrate was measured through the threshold voltage shift ( $V_t$  shift) of an electrically erasable programmable read-only memory (E<sup>2</sup>PROM) transistor. Initialized E<sup>2</sup>PROM wafers were exposed to the ECR plasma for 5 min, and the  $V_t$  shift was subsequently measured.<sup>10,13</sup>

Low-frequency rf bias of 600 kHz was supplied to the substrate in this experiment.<sup>11</sup> By using an rf bias frequency of more than 700 kHz, negative self-bias increases rapidly with frequency. The self-bias rapidly decreases to below 600 kHz.<sup>11</sup> Self-bias voltage is caused by the mobility difference between ions and electrons. At higher frequencies over 600 kHz, positive ions cannot follow the electric field due to their large mass, resulting in a large number of electrons accumulating on the substrate.<sup>11</sup> As a result, a large negative charge accumulates on the substrate and produces a negative self-bias. Conversely, at lower frequencies under 600 kHz, ions can be directly inserted from the plasma to the substrate since ions can follow rf oscillation, resulting in a reduction of self-bias on the substrate.

Figure 1 shows  $V_t$  shift as a function of the pulse interval. The  $V_t$  shift decreases as pulse interval increases to 100  $\mu\text{s}$ . The rapid decrease in  $V_t$  shift corresponds to the generation of negative ion density in the afterglow plasma. We have reported time variations of negative ion density in the after-glow plasma estimated from the Bohm criterion using a Langmuir probe.<sup>13</sup> Negative ion density increases monotonically until it reaches a maximum at 45  $\mu\text{s}$ . Generally, since Cl<sub>2</sub> plasma has an attachment cross section at a low electron temperature of a few eV, the negative ions cannot be generated in the low-pressure discharge because of their high electron temperature. However, in the afterglow plasma, electron temperature rapidly decreases and a large number of negative

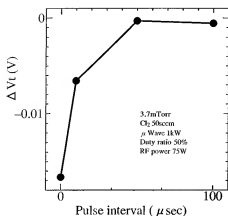


FIG. 1. Threshold voltage shift of E<sup>2</sup>PROM as a function of pulse interval.

ions is generated. The density of negative ions is about 9 times greater than that of electrons in the afterglow plasma at a period of 50  $\mu$ s. The plasma consists mainly of both negative and positive ions under these conditions. Negative and positive ions can both be accelerated by using a low-frequency rf bias of 600 kHz. Positive ions are then attracted to the surface during the negative rf cycle, and negative ions during the positive cycle. So the surface is quickly neutralized. Thus charge accumulation on the substrate can be reduced by enlarging the pulse interval to 50  $\mu$ s, as shown in Fig. 1. Therefore, charge-free etching processes can be accomplished by positive and negative ions in the pulsed plasma even at high density and low pressure.

It has been reported that the charge build up is higher in the center of the wafer and lower at the edge of the wafer such as in conventional ECR source because of plasma nonuniformity.<sup>13</sup> Figure 2 shows the radial distribution of the threshold voltage shift of an E<sup>2</sup>PROM on a six-in.-diameter substrate. The highest build-up of charge is observed in the center of the wafer during continuous discharge. According to this result, compact ECR source produces nonuniform plasma on the substrate during continuous discharge. Conversely, the distribution of  $V_t$  shift on the substrate becomes uniform when the 600 kHz rf biased pulsed plasma is used. In the pulse-time modulated plasma, positive, and negative ions are not trapped by the magnetic fields and move by the

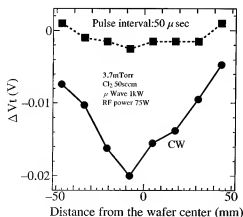


FIG. 2. Radial distribution of  $V_t$  shift of E<sup>2</sup>PROM.

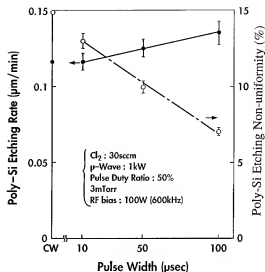


FIG. 3. Poly-Si etching uniformity as a function of pulse width.

ambipolar diffusion, whereas electrons are trapped by the magnetic fields and generate nonuniform plasma in continuous discharge. As a result, pulse-time modulated plasma creates uniform potential distribution. In gate poly-crystalline etching with 600 kHz rf bias, etching uniformity is also improved by pulse-time modulated plasma at a pulse interval of more than 50  $\mu$ s,<sup>14</sup> as shown in Fig. 3. As a result, a uniform and charge less process can be achieved using pulse-time modulated plasma.

In summary, pulse-time modulated ECR plasma with low-frequency rf bias makes it possible to eliminate charge surface effects with positive and negative ions. These characteristics are explained by the lower electron temperature and large number of negative ions. Charge-free etching processes can be accomplished even in high density and low pressure plasma. Additionally, uniformity can be improved by pulse-time modulated plasma.

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